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# Like Sign Top Pair Production via $e^+e^- \rightarrow h^0 A^0 \rightarrow tt\bar{c}\bar{c}$ <sup>1</sup>

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## Abstract

We discuss the possibility and likelihood that one may observe *like sign* top quark pair production at the Linear Collider. In general two Higgs models, flavor changing couplings involving top quark could be quite sizable. Exotic neutral Higgs bosons may decay dominantly via  $t\bar{c}$  or  $\bar{t}c$  channels. At the linear collider,  $e^+e^- \rightarrow h^0 A^0$  or  $H^0 A^0$  production processes could lead to  $b\bar{b}t\bar{c}$ ,  $W^+W^-t\bar{c}$  or  $tt\bar{c}\bar{c}$  (or  $\bar{t}tcc$ ) final states. These would mimic  $T$ - $\bar{T}$  mixing effect, except that  $T$  mesons do not even form.

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# 1 Introduction

In the previous workshop in Waikola, Hawaii, I presented a talk on searching for  $t \rightarrow ch^0$  decay at NLC.<sup>1</sup> Since then, the top quark has been found. With  $m_t \simeq 175$  GeV, we find that  $\text{BR}(t \rightarrow ch^0)$  cannot be more than 1%,<sup>2</sup> which is a relatively tough decay mode to study. Interest in Higgs boson induced flavor changing neutral couplings (FCNC) has also grown: 1) Lingering possibility of  $m_t < M_W$ ;<sup>3</sup> 2) Lepton number violation;<sup>4</sup> 3)  $CP$  violation;<sup>5,6,7</sup> 4)  $D^0 - \bar{D}^0$  mixing and rare  $D$  decays;<sup>7,8</sup> 5) Generic  $tcZ^0$  couplings<sup>9</sup> and effect on  $bsZ$  coupling;<sup>10</sup> 6) FCNC Higgs loop induced  $e^+e^- \rightarrow \gamma^*, Z^* \rightarrow t\bar{c}$  transition;<sup>11</sup> 7) Tree level  $\mu^+\mu^- \rightarrow$  neutral scalars  $\rightarrow t\bar{c}$ .<sup>12</sup>

We are concerned here with the last two items. Our theme is about the possibility of observing  $e^+e^- \rightarrow h^0 A^0 \rightarrow t\bar{t}\bar{c}c$  or  $\bar{t}tcc$ , namely, *like sign top pair production at linear colliders*. In the following, let us first see how it occurs, then contrast it with the work of Atwood, Reina and Soni, refs. 11 and 12.

## 2 The Model

Consider the existence of two Higgs doublets,  $\Phi_1$  and  $\Phi_2$ . The ‘‘Natural Flavor Conservation’’ (NFC) condition of Glashow and Weinberg<sup>13</sup> dictates that there be just one source of mass for each fermion charge type, usually implemented via discrete symmetries. For example, under  $\Phi_1 \rightarrow \Phi_1, \Phi_2 \rightarrow -\Phi_2$ , one has

$$\begin{aligned} \text{Model I :} \quad & u_R \rightarrow u_R, \quad d_R \rightarrow d_R, \\ \text{Model II :} \quad & u_R \rightarrow u_R, \quad d_R \rightarrow -d_R. \end{aligned} \tag{1}$$

In these models, called the ‘‘Standard 2HDM(s)’’, one has  $\lambda_f \propto m_f$ , hence the Yukawa and mass matrices are simultaneously diagonalized, and neutral scalar bosons are flavor diagonal *by construction*. Model II is popular since it is realized in the minimal supersymmetric standard model (MSSM). Note also that  $v_1 \equiv \langle \phi_1^0 \rangle$  and  $v_2 \equiv \langle \phi_2^0 \rangle$  are distinct because of the discrete symmetry, hence the familiar  $\tan \beta \equiv v_1/v_2$  appears in these models as a physical parameter.

Without imposing the NFC condition, i.e., without imposing the discrete symmetry of eq. (1), one would have *two* Yukawa coupling matrices,  $\lambda_f^{(1)}$  and  $\lambda_f^{(2)}$ , which in general are not proportional to the one and only mass matrix  $m_f$ . Thus,  $\lambda_f^{(1)}$  and  $\lambda_f^{(2)}$  in general cannot

be simultaneously diagonalized with  $m_f$ , hence  $\phi_1^0$  and  $\phi_2^0$  would induce FCNC at tree level. Historically, this problem lead Glashow and Weinberg to advocate<sup>13</sup> the necessity of NFC.

With spontaneous  $CP$  violation, in general<sup>5</sup>  $\arg(v_1/v_2) \neq 0$  since both  $v_1$  and  $v_2$  are complex, and  $\tan\beta = v_1/v_2$  remains a physical parameter. We shall, however, assume  $CP$  invariance and take both  $v_1$  and  $v_2$  to be real. In this case, a linear redefinition of  $\Phi_1$  and  $\Phi_2$  allows one to choose one doublet to be the “mass giver”, which develops a vacuum expectation value, while the other doublet has zero vacuum expectation, viz.<sup>14</sup>

$$\langle\phi_1^0\rangle = \frac{v}{\sqrt{2}}, \quad \langle\phi_2^0\rangle = 0. \quad (2)$$

In this way,  $\tan\beta$  is rotated away by the freedom to make linear redefinitions, and  $\text{Re}\phi_1^0$  is the “standard neutral Higgs”, except that it is *NOT* a mass eigenstate. In the basis of eq. (2) and ignoring leptons, one readily sees that

$$\left(m_i^{(u)}\bar{u}_{iL}u_{iR} + m_i^{(d)}\bar{d}_{iL}d_{iR}\right) \left(1 + \frac{\sqrt{2}}{v}\text{Re}\phi_1^0\right), \quad (3)$$

is flavor diagonal, however, for  $\Phi_2$  Yukawa couplings, we have

$$\begin{aligned} & \left(\bar{u}_L\xi^{(u)}u_R + \bar{d}_L\xi^{(d)}d_R\right) \text{Re}\phi_2^0 + \left(-\bar{u}_L\xi^{(u)}u_R + \bar{d}_L\xi^{(d)}d_R\right) \left(i\text{Im}\phi_2^0\right) \\ & \left(-\bar{d}_LV^\dagger\xi^{(u)}u_R\right) \phi_2^- + \left(\bar{u}_LV\xi^{(d)}d_R\right) \phi_2^+ + H.c. \end{aligned} \quad (4)$$

where  $\xi^{(u,d)}$  is in general *not* diagonal. We take  $V^{(\dagger)}\xi \simeq \xi$ , since the KM matrix  $V \simeq 1$ .

One may think<sup>14</sup> that the  $\Phi_2$  Yukawa couplings  $\xi^{(u,d)}$  could be completely general. However, taking cue from  $V \simeq 1$ , there is a weaker form, in fact a more *natural* one, for realizing “natural flavor conservation”. Cheng and Sher observed<sup>15</sup> in 1987 that, with the ansatz

$$\xi_{ij} \sim \frac{\sqrt{m_i m_j}}{v}, \quad (5)$$

FCNC involving lower generation fermions are naturally suppressed, without the need to push FCNC Higgs boson masses way beyond the *v.e.v.* scale. This is more natural than NFC in the following sense. Compared to the time when Glashow and Weinberg proposed the NFC condition, we now know that  $V \simeq 1$ . In addition, there are two seemingly related hierarchies in nature, namely the hierarchies in masses and KM mixing angles:

$$\left\{ \begin{array}{l} m_1 \ll m_2 \ll m_3, \\ |V_{ub}|^2 \ll |V_{cb}|^2 \ll |V_{us}|^2 \ll 1, \end{array} \right. \quad (6)$$

hence, since the KM matrix  $V$  measures the “difference” between the  $u_L$  and  $d_L$  diagonalisation matrices, one expects from naturalness that

$$\xi_{ij} = \mathcal{O}(V_{i3}V_{j3}) \frac{m_3}{v}, \quad (7)$$

unless fine-tuned cancellations are implemented. It was from this perspective that we emphasized<sup>2</sup> the pertinence and importance of FCNC Higgs induced transitions involving the heaviest quark, the top. Before we turn to low energy constraints, some further formalism is necessary.

So far we have been in the “weak” basis. We need to work in the (scalar) mass basis, which is determined by the Higgs potential  $V(\Phi_1, \Phi_2)$ . In fact, we need not care about the details of  $V(\Phi_1, \Phi_2)$ , since electric charge and  $CP$  invariance dictates that only  $\text{Re } \phi_1^0$  and  $\text{Re } \phi_2^0$  can mix, that is

<u>Gauge basis</u>		<u>Mass basis</u>
$\text{Re } \phi_1^0, \text{Re } \phi_2^0$	$\implies$	$H^0, h^0$
$\text{Im } \phi_2^0$	$\longrightarrow$	$A^0$
$\phi_2^\pm$	$\longrightarrow$	$H^\pm.$

(8)

The effect of the Higgs potential  $V(\Phi_1, \Phi_2)$  can be summarized in the rotation

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \sqrt{2} \text{Re } \phi_1^0 \\ \sqrt{2} \text{Re } \phi_2^0 \end{pmatrix}, \quad (9)$$

where the neutral scalar rotation angle  $\sin \alpha$  is a physical parameter of the model. In the limit that  $\sin \alpha \rightarrow 0$ , one has

$$\begin{cases} H^0 & \rightsquigarrow & \sqrt{2} \text{Re } \phi_1^0 \\ h^0 & \rightsquigarrow & \sqrt{2} \text{Re } \phi_2^0 \end{cases} \quad (\sin \alpha \longrightarrow 0), \quad (10)$$

where  $H^0$  is now the “standard” Higgs boson with flavor diagonal couplings, while  $h^0$  in this limit has general Yukawa couplings (subject to eqs. (5) or (7)) but does not couple to vector bosons or charged Higgs bosons. We note that our convention here for  $H^0$  and  $h^0$  differs from the usual convention in MSSM.

In the following, we shall take the scenario of eqs. (5) or (7) for Yukawa couplings, calling it Model III, and concentrate on consequences of the limiting case of eq. (10), which is also the simplifying assumption taken in refs. 11, 12 and 14. In the end, the consequences of  $\sin \alpha \neq 0$  will also be discussed.

### 3 Low Energy Constraints

Low energy FCNC processes involve external quarks belonging to lower generations. One readily sees from eqs. (5) or (7) that constraints on Higgs masses in Model III are far less stringent than in Models I and II. Specifically, important constraints come from  $d$  type quark sector and charged leptons.

$K-\bar{K}$  and  $B-\bar{B}$  mixings were considered by Cheng and Sher<sup>15</sup> and Sher and Yuan<sup>16</sup>, assuming eq. (5), leading to a not so stringent bound of  $m_{h^0} \gtrsim 80$  GeV for  $h^0$ , and a somewhat more stringent bound on  $A^0$ . Note, however, that the mass bound would weaken if  $\xi$  is weaker than that given by eq. (5).

As originally noted by Bjorken and Weinberg<sup>18</sup>, because of the need to have 3 chirality flips, the  $h^0$  or  $A^0$  induced one-loop contribution to  $\mu \rightarrow e\gamma$  is rather suppressed. At two-loop order, then, the one-loop effective scalar- $\gamma$ - $\gamma$  coupling induces  $\mu \rightarrow e\gamma$  transition with just 1 chirality flip, allowing this process to dominate over the one-loop process. For  $m_t \simeq 175$  GeV, we find<sup>17</sup> that  $m_{h^0, A^0} \gtrsim 150$  GeV, i.e. of order  $v$  scale, which is quite reasonable, and roughly agrees with the  $K-\bar{K}$  and  $B-\bar{B}$  mixing bounds.

Within Model II and to leading-log order in QCD corrections, CLEO finds<sup>19</sup>  $m_{H^+} \gtrsim 250$  GeV. This lower bound is specific to Model II because of a  $\tan\beta$  independent contribution.<sup>20</sup> In Model III, bounds could weaken because of the remaining freedom in  $\xi^{(u)}$  and  $\xi^{(d)}$ . Furthermore, it has been argued<sup>21</sup> that inclusion of next-to-leading order QCD corrections tends to soften the bound. Thus, we take  $m_{H^+} \gtrsim 150 - 250$  GeV as a reasonable lower bound. This bound is rather consistent with the bound on FCNC neutral scalar bosons.

The upshot is, it is rather likely that

$$v \sim m(\text{FCNC Higgs}) \gtrsim m_t. \quad (11)$$

### 4 Decay Scenario and Production Processes

There is no  $A^0 VV$  coupling to start with, where  $V = W$  or  $Z$ . In the limit of eq. (10), i.e.  $\sin\alpha \rightarrow 0$ , there is also no  $h^0 VV$  coupling. Taking at face value the lower bound of eq. (11), we restrict ourselves to the kinematic domain of

$$200 \text{ GeV} < m_{h^0, A^0} < 2m_t \simeq 350 \text{ GeV}, \quad (12)$$

then  $h^0$  and  $A^0$  can only decay via  $t\bar{c}$  (or  $\bar{t}c$ ) and  $b\bar{b}$ . We note that  $2m_t \simeq 350$  GeV is roughly the Higgs boson mass reach for a 500 GeV Linear Collider (NLC). The lower range of 200 GeV is chosen such that  $h^0, A^0 \rightarrow t\bar{c}$  decay is not overly restricted by phase space. That is,

$$\frac{\Gamma(h^0, A^0 \rightarrow t\bar{c} + \bar{t}c)}{\Gamma(h^0, A^0 \rightarrow b\bar{b})} \cong \frac{2\xi_{ct}^2}{\xi_{bb}^2} \left[1 - \frac{m_t^2}{m_{h^0, A^0}^2}\right]^2 \gtrsim 2 \frac{m_c m_t}{m_b^2} \left[1 - \left(\frac{175}{200}\right)^2\right]^2 \gtrsim 1.5. \quad (13)$$

Because of the large top quark mass, the first factor is of order 25 and large. The second phase space factor increases rapidly for  $m_{h^0, A^0} > 200$  GeV. We therefore conclude that, for  $m_{h^0, A^0} \in (200, 350)$  GeV, which is a very reasonable domain,  $h^0, A^0 \rightarrow t\bar{c} + \bar{t}c$  could likely be dominant over the  $b\bar{b}$  mode.

The production processes are rather standard. Again, in the limit of eq. (10) with  $\sin \alpha \rightarrow 0$ , the only neutral Higgs boson that couples to vector boson pairs is the “standard”, flavor diagonal  $H^0$  boson. Thus, the processes

$$e^+e^- \rightarrow Z^* \rightarrow H^0 Z^0, \quad (14)$$

$$e^+e^- \rightarrow \nu\bar{\nu} + H^0 \quad (WW \text{ fusion}), \quad (15)$$

are both  $\propto \cos \alpha$  in amplitude, and would appear to be completely standard. The nonstandard  $h^0$  boson would not be produced since it is  $\propto \sin \alpha$  in amplitude. However, as is well known, the associated production process

$$e^+e^- \rightarrow Z^* \rightarrow h^0 A^0 \quad (16)$$

is also  $\propto \cos \alpha$  in amplitude, and has a cross section similar to the process of eq. (14), except for difference in phase space and the transverse  $Z$  contribution proportional to  $M_Z^2/s$ . Since  $h^0, A^0 \rightarrow t\bar{c} + \bar{t}c$  is dominant over  $b\bar{b}$ , and because of the real field nature of  $h^0$  and  $A^0$  (and  $CP$  conservation), they each decay to  $t\bar{c}$  and  $\bar{t}c$  with equal weight. Thus, for the process of eq. (16), one could find 50% of the cross section going into *like sign top pair* events, namely,

$$\sigma(e^+e^- \rightarrow tt\bar{c}\bar{c} + \bar{t}tcc) \sim 0.5 \times \sigma(e^+e^- \rightarrow h^0 A^0). \quad (17)$$

There is one special process that deserves mentioning. It is now accepted that having back-scattered laser beams to convert linear  $e^+e^-$  colliders into effective  $\gamma\gamma$  colliders of almost equal energy is something highly desirable<sup>22</sup> when the NLC is built. The chief reason is the interest in *measuring* the  $H \rightarrow \gamma\gamma$  width, because of its sensitivity to beyond the standard model effects.<sup>23</sup> In the case of eq. (10), only the top contributes, with

$$\sigma(\gamma\gamma \rightarrow h^0, A^0) \sim 1 \text{ fb}, \quad (18)$$

which provides for clean FCNC single top production.

## 5 Rough Numbers and Background

For the mass range of eq. (12) with  $m_{A^0} > m_{h^0}$ , we list in Table 1 the number of events  $\mathcal{N}(h^0 A^0)$  for a 500 GeV linear collider with  $\int \mathcal{L} dt = 50 \text{ fb}^{-1}$ .

Table 1: Number of events in  $h^0 A^0$  channel for 500 GeV NLC at  $50 \text{ fb}^{-1}$ .

$m_{A^0}$ (GeV)	200	250	300	200	250	300	200	250
$m_{h^0}$ (GeV)	100	100	100	150	150	150	200	200
$\mathcal{N}(h^0 A^0)$	1100	750	600	900	500	150	500	200

It is clear that, when phase space permits, one expects the raw number of events at the  $10^3$  order. In contrast,  $H^0 Z^0$  associated production results in  $\sim 3 \times 10^3 - 500$  events for the mass range  $m_{H^0} \in (150, 300) \text{ GeV}$ . We list the number of potential background events in Table 2.

Table 2: Number of raw events in potential background modes.

$\mathcal{N}(t\bar{t})$	$\mathcal{N}(W^+ W^-)$	$\mathcal{N}(Z^0 Z^0)$
$\sim 30,000$	$\sim 400,000$	$\sim 30,000$

From the last two columns of Table 1, taking  $\mathcal{N}(h^0 A^0)$  to be of order 500, one expects of order 250  $t\bar{t}\bar{c}\bar{c}$  or  $t\bar{t}cc$  events, resulting in  $\sim 12$  signal events in the

$$e^+ e^- \longrightarrow \ell^\pm \ell'^\pm + \nu\nu + 4j \quad (19)$$

channel, where the 4 jets have flavor  $bb\bar{c}\bar{c}$  or  $\bar{b}\bar{b}cc$ . With a good detector, in part thanks to the large top quark mass, this distinctive signature has seemingly *no background*. In contrast, single  $\ell + \nu + 6j$  events or opposite sign dilepton events from  $t\bar{t}\bar{c}\bar{c}$  final states would be swamped by background listed in Table 2, which are orders of magnitude higher. In particular, standard  $e^+ e^- \rightarrow t\bar{t}$  pair production with additional gluon radiation may be especially irremovable.

## 6 Discussion

Although like sign top pair production is quite intriguing, the limiting case of eq. (10) may be a little extreme. Loosening the condition so  $\sin \alpha \neq 0$  results in  $H^0 - h^0$  mixing. Both

$H^0 Z^0$  and  $h^0 Z^0$  associated production become possible, with the respective weights of  $\cos^2 \alpha$  and  $\sin^2 \alpha$ . Assuming that  $\sin^2 \alpha < \cos^2 \alpha$ , we note that  $H^0$  width is in general still large, since it is dominated by  $H^0 \rightarrow W^+ W^-$  and  $ZZ$ , and  $H^0 \rightarrow t\bar{c} + \bar{t}c$  would be rather rare. For the  $e^+ e^- \rightarrow h^0 Z^0$  process, the cross section is suppressed by  $\sin^2 \alpha$ , but, when  $\sin^2 \alpha$  grows, the  $h^0 \rightarrow t\bar{c}$  mode is quickly overwhelmed by the  $h^0 \rightarrow VV$  modes, and again the effective cross section is reduced. In any case, one expects some events in  $Z + t\bar{c}$  production, with large fraction into  $b\bar{b}t\bar{c}$ .

We have also listed in Table 1 the possibility of  $m_{A^0} > m_t$  but  $m_{h^0} < m_t$ . If such is the case, we expect  $h^0 \rightarrow b\bar{b}$ , and again we have  $e^+ e^- \rightarrow b\bar{b}t\bar{c}$ , with a different  $b\bar{b}$  pair mass. With good  $b$ -tagging efficiency, these modes should not be difficult to study.

We now compare with the results of Atwood, Reina and Soni. For  $e^+ e^- \rightarrow \gamma^*$ ,  $Z^* \rightarrow t\bar{c}$  via  $h^0$ ,  $A^0$  loop effects, Atwood et al.<sup>11</sup> find less than 0.1 event for a 500 GeV NLC with  $\int \mathcal{L} dt = 50 \text{ fb}^{-1}$ . For heavy  $h^0$  and  $A^0$  where our processes are kinematically forbidden, the loop induced cross section also goes down by another order of magnitude.<sup>11</sup> Thus, this process is unlikely to be observable at the NLC. Loop suppression in this case is no match against normal tree level processes that we discuss.

For  $\mu^+ \mu^- \rightarrow h^0$ ,  $A^0 \rightarrow t\bar{c} + \bar{t}c$ , the process occurs at tree level and has a sizable cross section.<sup>12</sup> But in the scenario (of eq. (10)) taken, because of the absence of  $h^0$ ,  $A^0 \rightarrow VV$  decay mode, one needs a rather fine stepped energy scan because of the narrowness of the  $h^0$  and  $A^0$  width. Together with the uncertainty of whether a high energy, high luminosity  $\mu^+ \mu^-$  collider can be realized, we feel that this process is less straightforward to study than the processes we discuss for the NLC. In particular, it may be even less promising than searching for  $\gamma\gamma \rightarrow h^0$ ,  $A^0$  at the NLC.

The signature of like sign top pair production is rather analogous to producing  $B^0 B^0$  or  $\bar{B}^0 \bar{B}^0$  final states via  $B^0 \bar{B}^0$  pair production followed by  $B^0 - \bar{B}^0$  mixing. However, for  $m_t \simeq 175 \text{ GeV}$ , top mesons (be it  $T_u^0$  or  $T_c^0$ ) do not even form! The reason that we get like sign top pair production here is due to the real neutral scalar field nature of  $h^0$  and  $A^0$ , which circumvents the usual condition of associated production of  $t\bar{t}$  pairs in most processes. Since  $h^0$  and  $A^0$  contribute to  $B - \bar{B}$  mixings, the like sign top pair production effect reported here is related to neutral meson–anti-meson mixing phenomena. We know of no other way to make  $tt$  or  $t\bar{t}$  pairs in an  $e^+ e^-$  collider environment.



## 7 Summary

In the context of a two Higgs doublet model without imposing NFC condition, neutral scalar bosons in general has FCNC couplings. We have presented the case where  $h^0, A^0 \rightarrow t\bar{c} + \bar{t}c$  could be the dominant decay mode, for the rather reasonable mass range  $m_{h^0, A^0} \in (200, 350)$  GeV. The most intriguing consequence is the possibility of detecting like sign top pair production via  $e^+e^- \rightarrow h^0 A^0 \rightarrow tt\bar{c}\bar{c}$  or  $\bar{t}\bar{t}cc$ . One may also detect single top FCNC production via  $\gamma\gamma \rightarrow h^0, A^0 \rightarrow t\bar{c} + \bar{t}c$ . The situation becomes richer if  $\sin\alpha \neq 0$ , where one has  $h^0$ - $H^0$  mixing, leading to  $Z + t\bar{c}$  events. The situation could get even richer if  $CP$  is violated in Higgs sector, where one has  $h^0$ - $H^0$ - $A^0$  mixing. Since the Higgs sector of minimal SUSY (MSSM) is flavor diagonal, *observation of the signatures reported here would rule out MSSM*. We urge experimental colleagues to study the signal vs. background issue carefully.

## 8 References

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